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UNDERGROUND AMMUNITION STORAGE

Blast Propagation in the Tunnel System

Report II A

CHAMBER PRESSURE

SEP 1975

FORSVARETS BYGNINGSTJENESTE

Norway

AD-A027064

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AC/258-NO(ST)IWP/32

Vår referanse 808/76/B/KSLARAU/GK/BKB/738 C

Dato 6. ~~JUNI~~ JULY 1976

Tidligere referanse

For Delegates AC/258 Storage Sub-Group and
Underground Storage Sub-Group

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References: (1) ASESB - o letter dated 15th January 1971
(2) KSLARAU letter dated 14th April 1971

1. At the May 1976 meeting of the AC/258 Underground Storage Sub-Group the US Delegate requested a written statement from the Head of the Norwegian Defence Construction Service that technical reports submitted as AC/258-NO(ST)IWP/ could be submitted to the Defence Documentation Center for disseminatio[n] unless otherwise stated.

2. Firstly, I would use this opportunity to discharge my referenc[e] letter (2) to the Chairman ASESB with rather strict limitation[s] for the dissemination of NO technical reports submitted to the AC/258 Group. Since experiance showed that these previous procedures were not adequate, I proposed at the end of 1975 to the Ministry of Defence revised terms of reference and working procedures with respect to Norwegian representation in NATO Group AC/258. This proposal was accepted and implemented by MOD letter 850/76/B/FD.IV.12/204.14/AC/258 dated [illegible]th January 1976.

3. With respect to your specific question the following procedur[es] from the new MOD prescriptions are relevant:

a. Norwegian statements/contributions etc to the AC/258 Group is normally to be coordinated and given by the appointed NO representative during AC/258 meetings and/or in written submissions. If such written statements represent formal national position, ie beyond AC/258-WP or IWP status, they are to be forwarded through the MOD, otherwise only a copy is submitted to the MOD.

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- 4 -

coordination and formal position. Such reports are forwarded by the organization concerned to the appointed NO Representative for further submission to AC/258 Key Delegates. Such reports may be disposed by other NATO countries according to the distribution statement "Approved for public release; distribution unlimited" unless otherwise specified in the report itself and in AC/258-WP or NO(ST)IWP/.... cover letter."

4. Since the US request was related to AC/258-NO(ST)IWP/27 with the five NDCS Underground Reports, I have informed Mr A Jenssen. On behalf of the NDCS he has confirmed that the dissemination statement of paragraph 3 above is correct.

G Kyrkjebø

G Kyrkjebo
Lt Colonel
Norwegian Representative to AC/258

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Blast Propagation in the Tunnel System.

Report II A.

CHAMBER PRESSURE

(10) A. T. Skjeltorp, T. Hegdahl A. Jenssen

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UNDERGROUND AMMUNITION STORAGE

Blast Propagation in the Tunnel System

Report II A

CHAMBER PRESSURE

A.T. Skjeltorp, T. Hegdahl, and A. Jenssen

September 1975

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SUMMARY

The purpose of the present work was to examine the pressure-time history for detonation and burning of various explosives in confined regions (chambers). In the detonation tests, a systematic study was performed for three types of explosives (TNT, PETN, and DYNAMITE) for different loading densities and chamber venting.

Four additional explosives (AN/FO, RDX, ALUMIT, and COMP.B) were also tested over a limited range of loading densities in a closed chamber. To determine the maximum "chamber pressure", carefully designed electrical filters were employed to remove the high frequency ringing in the pressure-time recordings. The results compare favourably with recent calculations of post-detonation pressures in closed and vented chambers.

Some preliminary tests were performed to determine the ignitability for the explosives used in the detonation tests using the closed bomb method. For one explosive (PETN), the transition from burning to detonation was established.

1. INTRODUCTION

This report is the second in a series of five /1/, /2/ describing the results from an extensive series of model tests on underground ammunition storage.

The main objectives of the experiments discussed in this report were to determine the pressure-time history from an explosive charge detonated in chambers varying:

(a) loading density
(b) venting
(c) type of explosive (TNT, PETN, AN/FO, RDX, ALUMIT, DYNAMITE and COMP.B)

and to compare our results with:

(d) theoretical work
(e) other experiments.

In addition, this report also describes some preliminary experiments to determine the ignitability for various types of explosives (TNT, PETN, AN/FO, RDX, ALUMIT, DYNAMITE and COMP.B) using the closed bomb method. The basic objective for these ignitability tests was to determine the hazard of detonation for various explosives when these are burned in a closed system. If one could predict this transition from burning to detonation, a safer approach to storage could be adopted.

The pressure-time history in the chambers was found using standard measurement techniques, involving the use of piezoelectric gauges. Unfortunately, the pressure actually recorded by a pressure gauge, may be subject to ambiguous parameters (e.g. maximum "chamber pressure") and this will be discussed in Sec.2. The maximum gas pressure which is adopted is reasonably well defined and can be related to experimental and theoretical work by others, which will be reviewed briefly in Sec.3. This is followed by a short description of our particular experi-

mental set-up in Sec.4. The results are presented in Sec.5, including comparison with existing experimental and theoretical data, and the principal results are finally summarized in Sec.6.

2. Chamber Pressure

The pressure-time recording in Fig 2.a shows the typical behaviour in a closed bomb detonation. This was obtained with our particular experimental set-up using a high resolution piezoelectric pressure gauge (Sec.4.3). The initial spike is due to the incident (free air) shock wave hitting the wall. The subsequent peaks are due to the multiple reflected waves from the walls similar to an organ pipe resonance in the cylindrical chamber /3/. After a relatively short time, an equilibrium pressure is reached, but the pressure will decrease approximately exponentially due to heat losses and leaks. Clearly, the detailed initial pressure-time history actually recorded is critically determined by the shape of the chamber, explosive charge (location and/or distribution) and the location of the gauge. It is therefore difficult to define a maximum "chamber pressure" and different interpretations are also found in literature. For example, Brode /4/ calculates a "wall pressure" similar to the pressure actually recorded by a pressure gauge as shown in Fig 2.b. Unfortunately, this definition is somewhat ambiguous for most practical purposes because of the experimental geometry mentioned.

An average pressure, or gas pressure, as indicated in Fig.2.a can be evaluated with reasonable accuracy using carefully designed electrical filters as discussed in Report I, and this definition also conforms with most previously reported experimental and theoretical work.

It should be stressed that the initial spike in the actual pressure-time history will be significantly higher than the average peak pressure, (actual peak pressure ≃ reflected overpressure which may be 8 - 10 times higher than the average peak pressure) and may be quite destructive to the chamber

walls. In underground ammunition storage sites in rock, the destruction is expected to take place in the vicinity of flows and cracks in the rock, but there is at present very limited information on the propagation speed of such cracks. This is of current interest as recent large scale tests in Älvdalen /5/ and Raufoss /6/ produced large rock displacements of the overhead cover.

Pressure-time recordings in the case of the burning of explosives in a closed chamber, show a much smoother behaviour, (Fig.2.c), and the interpretation of a maximum chamber pressure is reasonably well defined here. However, the reproducibility is quite often poor. Minor changes in the igniting procedure may cause significant change in the pressure-time history.

3. PREVIOUS THEORETICAL AND EXPERIMENTAL WORK

3.1 Detonation of explosives in closed chambers

The pressure created in a closed chamber when an explosive charge is detonated is given approximately by:

$$p = (\gamma - 1) \cdot e \cdot Q/V, \qquad (3.1)$$

where

e is the energy released per unit weight by the detonation of the charge

Q is the charge weight

V is the chamber volume

$\gamma = c_p/c_v$, the ratio of the specific heats at constant pressure and constant volume of the gases involved in the explosion

γ and e depend on the loading density, Q/V, and the ambient gas in the chamber in a complicated way and are not readily estimated /3/.

Various theoretical calculations /3, 4, 7-15/ and measurements /3, 10, 11, 16-20/ of the pressure-time history of explosions in closed and partly closed chambers have shown that the underlying physical

models as well as the interpretation of the experimental results are very important. Proctor and Filler have recently developed an extensive computer code for calculating blast loading for 29 different explosives /8/ and their results are in excellent agreement with experimental data reported by Weibull for TNT /16/, James and Rowe for PETN and RDX/TNT /17/, and Filler for RDX/AL/WAX /3/.

Proctor and Filler originally based their calculations on ideal gas assumption, but this has recently been extended also to include real gas effects /29/.

Strømsøe /13/ has estimated the post-detonation pressure and temperature of TNT charges in an unvented chamber for a wide range of loading densities (0,2 to 270 kg/m3) also including real gas effects. The results from these calculations are practically the same as those for Proctor /29/.

In the experiments reported here variable venting was used, and the effect from this can be compared with Proctor and Filler's computer code which allows for variable venting.

Strømsøe has argued /28/ that the results from model tests using relatively small steel models may be quite misleading due to heat loss.

The present measurements of the chamber pressure with no venting, will give an experimental estimate of this effect.

Estimates have been made /8/, /14/ of the post-detonation temperature of charges in closed chambers, and it would have been interesting to verify these calculations experimentally. Temperature measurements were also planned in the present tests, but this was abandoned because of lack of suitable temperature sensors for the extreme conditions in question.

3.2 Burning of High Explosives in Closed Chambers

There is at present no safe theoretical way of estimating the

possibility of detonation of various explosives, caused by external effects. To obtain such information one has to do various classification tests as for example drop tests, friction sensitivity tests, or so-called closed bomb tests /21, 22/. It is of interest to classify the sensitivity of explosives and propellants when these are burned in confined storage, e.g. to predict the transition from fire to explosion in underground ammunition storage, and for this purpose the closed bomb technique is well suited. This was the basis for the preliminary experiments reported in this paper.

4. EXPERIMENTAL DETAILS

4.1 Chambers

Details of the chambers used in the detonation and burning tests are given in report I /2/. The most important data in the detonation tests, including chamber volumes, amount of venting and loading densities are summarized in Table 4.1a and details of the burning tests will be presented together with the experimental results in Sec.5.

4.2 Explosives

Characteristic data for the various explosives used in the present tests are given in Table 4.2a.

The explosives in the detonation tests were suspended in the middle of the cylindrical detonation chamber as shown in Fig. 4.2a and initiated with electrical blast cap no. 8, which has an equivalent TNT weight of about 1,5 g.

The explosive charges in the ignitability tests were put in a crucible on legs placed on the floor of the detonation chamber as shown in Fig 4.2b. The charge was ignited by the burning of tracer composition (Table 4.2a) in contact with the charge. The tracer composition was ignited using electrical heating. The use of black powder instead of tracer composition in these tests did not initiate a fire in all explosives tested.

4.3 Instrumentation

To measure the pressure-time history in the chamber, standard measurement techniques were used employing piezoelectric pressure transducers (Kistler model 6201) The transducers were protected from the heat by a piston of silicon oil mixed with graphite and silicon grease positioned in the chamber wall leading from the transducer to the inside of the chamber. (Fig. 4.2a). (See Report I, /2/).

The transducer signals were amplified using Kistler charge amplifiers and recorded on an Ampex FR 1300 A tape recorder. The maximum frequency response of this system was about 40 kHz, which proved to be sufficient for the present experiments (See Report I, /2/).

4.4 Data reduction

The average peak pressures for the detonation tests were evaluated using carefully designed electrical filters as discussed in Report I, /2/. In practice the pressure-time recordings were filtered at two frequencies (8 and 16 Hz). To obtain the true average peak pressure, the ratio between the maximum readings for the two filtered signals was multiplied by a correction factor. This factor which depended on the filter frequencies, was worked out under the assumption of an exponential pressure decay for the time-average chamber pressure.

The accuracy of this filtering procedure could be tested by changing the filter frequencies. This showed that this technique was reproducible to within about 5%, and the estimated average peak pressures should therefore correspond quite closely to the theoretically calculated chamber pressures.

5. EXPERIMENTAL RESULTS

The original pressure-time recordings for the closed bomb tests are reproduced in part B of report II, and chamber pressure recordings for variable venting in part B of reports III and IV.

5.1 Detonation

5.1.1 TNT

The results from the detonation tests of TNT are shown in Table 5.1a. Separate plots of the average peak pressure versus loading density for TNT for the various configurations (different chamber volumes and venting) did not show any systematic differences. Fig. 5.1a therefore shows the results without distinguishing between these configurations and taking the average of one to three shots. The error bars represent the combined uncertainties from experimental errors as well as errors in estimating the average peak pressure using the filters described in Sec.4.4. The results reported by Weibull /16/ are also included in this figure and in the region of overlap the agreement is very good.

The results of the calculations by Proctor /29/ and Strømsøe /13/ are not significantly different and are therefore drawn as one line in Fig. 5.1a. As may be seen, the general agreement between their calculations and the present results are well within experimental error.

Proctor and Filler's computer code also allows for variable venting and two special cases of their calculations /24/ of the total pressure-time history can be compared directly with the present experiments. This is shown in Figs. 5.1b and 5.1c.

As may be seen, there is good agreement considering the oscillations in the actual pressure-time trace. In particular, heat loss to the chamber walls (radiation and conduction) does not seem to play an important factor in these two special cases. An even better check of the heat loss is provided by the chamber pressure measurements with no venting. An example of this is shown in Fig. 5.1d for a TNT loading density of 11,6 kg/m^3.

As may be seen, there appears to be about a 15% initial pressure decrease in the first 20 ms/m (= $7/R_o$ = scaled time). This is followed by a relatively slow pressure decrease which can be described empirically as roughly

$$p(t) = p(t_o)\exp[-0{,}00023\ (t - t_o)/R_o]$$

where $p(t_o)$ and $p(t)$ is the average chamber pressure at times t_o and t, respectively. R_o is the radius of an equivalent spherical cavity, which is introduced to make the exponent dimensionless (In the present case R_o = 0,154 m, corresponding to V = 17300 cm^3). Over a typical scaled time $(t - t_o)/R_o$ = 20 ms/m, the pressure has therefore only dropped 0,5%.

For this typical model, the heat loss will therefore be of no practical importance. This appears to be conflicting with the conclusions reached in Ref. 28 from the calculations of the heat conduction loss. It should be noted that part of the pressure drop found in the present tests in fact may be due to small leaks in the detonation chamber (Report I, /2/). The pressure drop measured is therefore an upper limit for the effects from heat loss.

5.1.2 PETN

The average peak pressure versus density for PETN is listed in Table 5.1b and is shown in Fig.5.1e. The error bars represent the combined uncertainties from experimental errors as well as errors in estimating the average peak pressure using the filters described in Sec.4.4. The data appear to be evenly distributed around a straight line in the log-log plot and a least squares fit gives the relationship

$$p = 18{,}6\ (Q/V)^{0{,}84} \qquad (5.1b)$$

The experimental results reported by James and Rowe /17/, and the theoretical calculations by Proctor /29/ are also included in this figure. As may be

seen, there is fair agreement between these sets of data and the present results. The consistently lower pressure data reported by Gottlieb /10/ are probably due to his somewhat different interpretation of an average peak pressure. From a direct comparison between the two sets of data in Figs. 5.1a and 5.1e the experimental TNT equivalence of TETN will be calculated later (Sec. 5.1.5).

5.1.3 Dynamite

The average peak pressure versus loading density for dynamite is listed in Table 5.1c and is shown in Fig. 5.1f /25, 26/. The results reported by Rütz /27/ are also included in this figure. In the region of overlap it can be seen that the agreement is good.

So far no theoretical calculation has been carried out to predict the chamber pressure for dynamite. A rough estimate can be obtained using Eq. (3.1) with $e = 4 \times 10^7$ Joule/kg and an average value $\gamma = 1,2$. As expected, this relationship does reproduce the data qualitatively, but a more detailed calculation using Proctor and Filler's code would be most interesting.

Fitting the data points to a straight line in the log-log plot in Fig 5.1f, produces the relationship

$$p = 7{,}07\ (Q/V)^{1{,}06} \qquad (5.1c)$$

From a direct comparison between the two sets of data in Figs. 5.1a and 5.1f the experimental TNT equivalence of dynamite will be calculated later (Sec. 5.1.5).

5.1.4 Other explosives

The results for the remainder of the explosives, AN/FO, COMP.B., RDX and ALUMIT, are given in Table 5.1d and are shown in Fig. 5.1g. The pressures calculated by Proctor /24/ for AN/FO and RDX are also included in this figure. The large differences between theory and experiments may be due to experimental error. For AN/FO it can also be due to the relatively small charges

used in the tests. In this case the detonation wave inside the explosive may not have developed fully. These tests were rather limited, and quite a number of additional experiments over a wider range of loading densities are clearly called for.

5.1.5 TNT equivalence of PETN and dynamite

The experimental determination of the TNT equivalence of various explosives is notoriously difficult since it generally depends on the experimental conditions and the blast wave parameter one chooses as the basis for the comparison.

The closed bomb tests would therefore only serve as a special technique for this purpose. The TNT equivalence would then be the quantity of TNT required to produce the same average peak chamber pressure per unit quantity of explosive for which the determination of the TNT equivalence is required.

By comparing the results in Figs. 5.1a, 5.1e and 5.1f, the TNT equivalence of dynamite and PETN is obtained and this is shown in Fig 5.1h. It can be seen from this figure that the TNT equivalence depends on the loading density as expected. This is due to the fact that TNT, PETN and dynamite have quite different oxygen deficiencies (74%, 10% and 0% respectively), and the blast energy is strongly dependent on the ambient oxygen relative to this deficiency /3/.

The equivalent weights of PETN obtained from Proctor's computer code are also included in Fig. 5.1h.
These results seem to be in fair agreement with our data in the limited region of overlap. It is not possible in a systematic way to determine the TNT equivalence for the other explosives (AN/FO, COMP.B, and RDX) due to the limited number of tests.

5.2 Ignitability tests

The detailed results of the ignitability tests are reported elsewhere in part B of this Report, /2/. The characteristic data, chamber pressure, rise-time, and maximum rate of pressure rise are given in Tables 5.2a and 5.2b. The rise-time is defined as the time from the onset of a detectable pressure increase to the time where the pressure reaches its maximum value. (See Fig.2.c). The maximum rate of pressure rise is defined as the maximum slope in the pressure-time recording (See Fig.2.c).

Only the results for PETN are complete enough to show systematic trends in regard to peak pressure versus loading density. This is shown in Fig.5.2a together with the detonation tests discussed in Sec.5.1.1. As may be seen, the two curves approach each other as the charge density increases and reasonable extrapolation of the burning-curve shows that the two curves fall together for a loading density of about 50 kg/m^3 or an average peak pressure of about 500 bar. This pressure, therefore, would be a rough estimate of the transition pressure where the burning rate of the explosive is so high that one actually has a detonation. The 500 bar value for PETN would seem to be in the middle range of values reported for a number of explosives /21/.

From Table 5.2a it can also be seen that there is a dramatic change in the maximum rate of pressure rise beyond a loading density of about 10 kg/m^3. This is consistent with the sharp pressure increase at approximately the same loading density in Fig.5.2a.

The results for the burning of the six remaining explosives given in Table 5.2b are quite limited, and systematic trends are difficult to assert in this case. However, if the ignitability of the more rapidly burning substance is considered greater, it increases from left to right as follows: (AN/FO, ALUMIT), DYNAMITE, (TNT),

PETN, COMP.B, and RDX. In the case of AN/FO and ALUMIT there was no ignition using the tracer composition. The position of TNT in this sequence is also somewhat uncertain in that the loading density was somewhat higher for this explosive.

6. SUMMARY AND CONCLUSIONS

Our experimental results for the average peak pressure for detonation of TNT, PETN and DYNAMITE in a closed chamber are in good agreement with earlier theoretical and experimental work. The results for AN/FO, COMP.B and RDX do not show such good agreement, but the limited number of tests precludes any definite conclusions in this respect.

Direct comparison of the closed bomb data show that the TNT equivalents of PETN and DYNAMITE depend on the loading density. The use of one TNT equivalent for blast wave data in complicated structures will probably be somewhat ambiguous.

The burning of PETN in a closed chamber shows that the burning rate is characteristic of an explosion for pressures above about 500 bar (about 50 kg/m^3). The sequence of ignitability for a loading density of about 6 kg/m^3 for the seven explosives tested appears to be (AN/FO, ALUMIT), DYNAMITE, (TNT), PETN, COMP.B and RDX increasing from left to right with explosives in parentheses somewhat uncertain in this sequence. Quite a number of additional experiments with a wider range of loading densities for the explosives other than PETN are clearly called for to determine the possibility of detonation.

R E F E R E N C E S

1. The reports in Ref. 2 contain the main results whereas reports labeled II B, etc, contain the raw data in the form of pressure-time recordings and tabulated blast wave parameters.

2. A.T. Skjeltorp, T. Hegdahl, and A. Jenssen, "Underground Ammunition Storage I, II A, III A, IV A, and V A", Report nos. 80/72, 79/72, 81/72, 82/72, and 83/72. Norwegian Defence Construction Service (1975).

3. W.S. Filler, "Chamber Pressure Predictions for High Explosive Driven Blast Simulators", Proceedings 3rd International Symposium on Military Applications of Blast Simulators , Ernst-Mach-Institut, Freiburg, p. D7-1 (1972).

4. H.L. Brode and B.R. Parkin, "Calculations of the Blast and Close-In-Elastic Response of the Cavity Explosions in the Cowboy Program", J. Geog. Res., 68, 2761 (1963).

5. E. Abrahamsson, "Operation Block", Proceedings 4th International Symposium on Military Applications of Blast Simulation, AWRE, Foulness, England, p. D1.1 (1974).

6. E. Strømsøe, "Underground Explosion Trials at Raufoss 1968. Measurement of Air Blast Outside the Tunnel", Norwegian Defence Research Establishment, Rep. no. X-124.

7. J.F. Proctor, "Structural Analysis of NOL Explosion Testing Facilities", NOLTR 69-84 (1969).

8. J.F. Proctor and W.S. Filler, "A Computerized Technique for Blast Loads from Confined Explosions", Proceedings Fourteenth Annual Explosives Safety Board, Washington D.C., 1972) p. 99.

9. H.L. Brode, "Nuclear Explosion in Cavities", Rand Corp. Res. Mem. RM-3727 (1960).

10. J.J. Gottlieb, "Investigation of the Pressure After an Explosion in a Closed Vessel", Suffield Technical Paper no. 371 (1971).

11. J. Nagy, J.W. Conn, and H.C. Verakis, "Explosion Development in a Spherical Vessel", Bureau of Mines Rept. of Inv. 7279 (1969).

12. A. Zweifel,
"Druecke in einer geschossenen Kammer kurz nach der Detonation von Munition", Eidgenössische Technische Hochschule Zürich, Gruppe für Rüstungsdienste, Technische Unterabteilung 6, 3602 Thun, Switzerland (1972).

13. E. Strømsøe,
"Estimate of the Post-Detonation Pressure and Temperature of TNT-Charges in a Closed Chamber", Norwegian Defence Research Establishment, Technical Note no. X-222.

14. E. Strømsøe,
"An Estimate of the TNT Equivalence of PETN in Contained Explosions", Norwegian Defence Research Establishment, Technical Note no. VM-104.

15. R.G.S. Sewell, G.F. Kinney, and J.E. Sinclair,
"Internal Explosions in Vented and Unvented Chambers", Proceedings Fourteenth Annual Explosives Safety Seminar (Department of Defense Explosive Safety Board, Washington D.C., 1972) p. 87.

16. H.R.W. Weibull,
"Pressure Recorded in Partially Closed Chambers at Explosion of TNT Charges", Annals of the New York Academy of Sciences, Vol. 152, Art. 1, p. 357 (1968).

17. D.J. James and R.D. Rowe,
"Measurements of Steady Overpressure Loading on the Wall of a Spherical Cavity Resulting from the Detonation of a Single HE Charge at the Center", AWRE report no. E 3/64 (1964).

18. Hsj. Rytz,
"Druckversuche beim Verpuffen von porösen Nc-Pulvern und Trotyl", Eidgenössische Technische Hochschule, Zürich Switzerland (1972).

19. Hsj. Rytz,
"Druckversuche beim Verpuffen von Nitroguanidin, Hextro 60/40 (≅ Comp. B) und Hexogen (≅ RDX)", Eidgenössische Technische Hochschule, Zürich, Switzerland (1972).

20. J. Nagy, E.C. Seiler, J.W. Conn, and H.C. Verakis,
"Explosion Development in Closed Vessels", Bureau of Mines Dept. of Inv. 7507 (1971).

21. S. Wachtell,
"Prediction of Detonation Hazard in Solid Propellants", Proceedings from Symposium on Explosives and Hazards and Testing of Explosives, 145th National Meeting Am. Chem. Soc., Vol. 7, No. 3, p. 83 (New York, 1963).

22. V.M. Rogozhnikow *et al.*,
"Determination of the Ignitability of Explosives by the Monometric Bomb Method", Vzryvnoye Delo, no 68-65 (1970).

23. G.B. Kistiakowsky,
"Initiation of Detonation in Explosives", Third Symposium on Combustion Flame and Explosion Phenomena, (Williams and Wilkins, 1949).

24. J.F. Proctor, private communication.

25. These data were originally presented in Ref. 26 without using the special electrical filtering technique adopted for the present study (Sec. 4.4). There are therefore differences between the present results and the results in Ref. 26.

26. E. Flaten,
"Underground Ammunition Storage. Model Test to Investigate the Strength and Effectiveness of a Selfclosing Concrete Block". Report no. 76/72, Norwegian Defence Construction Service (1972).

27. Hsj. Rütz. Private communication.

28. E. Strømsøe, "Scaling of Underground Explosion and the Heat Loss Problem", Norwegian Defence Research Establishment, Technical Note no. VM-15 (1971).

29. James F. Proctor,
"Blast Loadings from an Internal Explosion", Naval Ordnance Laboratory, Silver Spring, preliminary report (1974).

TABLE 4.1a Summary of the detonation tests for various chambers, venting, explosives and loading densities

Series	a		b		c			d	e	
Chamber volume (cm^3)	7250		10900		15200			4300	17300	
Venting (cm^2)	35	70	35	70	35	70	140	0	0	81
Type of explosive	LOADING DENSITY (kg/m^3)									
TNT	1,6-3,4	1,8-65,8	4,3	4,6-68,0	1,6-67,5	4,7-48,8	3,3-16,6		11,6	
PETN								23,3-46,5	0,58-23,1	
AN/FO									11,6 -46,5	
RDX									11,6	
ALUMIT									11,6 -46,5	
DYNAMITE									11,6	5 -50
COMP. B									11,6	

TABLE 4.2a

Characteristic data for the explosives used in the experiments.

Explosive	Composition (parts by weight)	Specific density (g/cm^3)
TNT	Trinitrotoluene	1,54 (Pressed) d 0,8 (Flaked) e
PETN	Pentyl/Wax, 93,7/6,3	
AN/FO	Ammonium nitrate/Diesel oil 94,5/5,5	0,90 (Prills)
RDX	Cyclotrimetyl-enetrinitramine/Wax 97/3	0,85 (Granulated)
ALUMIT	Ammonium nitrate/Calciumnitrate a /Water/Gums/Al-powder, 40/30/10/10/10/	1,30 (Water gel)
DYNAMITE	Ammonium nitrate/Gums/Nitro-glycerin 20/80 b/Nitrocellulose/Dinol/Wood flour/Rye flour/Silica gel/Chalk, 62,2/0,4/26,67/1,35/8,00/1,00/0,20/0,09/0,09	1,45 (Gel consistence)
COMP.B	RDX/TNT/WAX, 59,5/39,5/1,0	1,70 (Strips)
Tracer Composition c	Magnesium powder/Micro Talc./PVC/Strontium nitrate, 34,4/5,6/5,6/54,4	

a Commercial type: 79% Calciumnitrate, 15% water, and 6% Ammoniumnitrate.

b 20% Nitroglycerin, 80% Nitroglykol.

c Used to initiate fire in the ignitability tests.

d Used in the detonation tests.

e Used in the ignitability tests.

Table 5.1a

DETONATION TESTS OF TNT

Chamber volume cm^3	Charge TNT g	Loading density kg/m^3	Chamber venting cm^2	Pressure bar	Shot no.
15200	25	1,6	35	38	29
7250	13	1,8	70	37	200
7250	23	3,2	35	49	36
15200	49,5	3,3	140	37	171
15200	50,5	3,3	70	36	177
15200	49,5	3,3	70	40	210
15200	49	3,3	70	54	211
7250	25	3,4	35	56	37
15200	60	3,9	35	50	11
7250	28	3,9	70	50	191
10900	46,5	4,3	35	57	31
10900	50	4,6	70	36	184
15200	51,5	4,7	70	55	77
10900	51	4,7	70	66	233
10900	51	4,7	70	66	233
10900	51	4,7	70	64	234
10900	52	4,8	70	48	185
7250	39	5,4	70	62	203
15200	244	16,1	70	179	178
15200	250	16,5	35	162	13
15200	250	16,5	35	145	14
15200	250	16,5	35	174	16
15200	252	16,6	140	168	172
7250	124,5	17,2	70	159	193
7250	125	17,3	70	172	192
7250	127	17,5	70	160	223
7250	128,5	17,7	70	185	204
7250	128,5	17,7	70	180	205
10900	243	22,3	70	191	187
10900	245	22,5	70	204	186
10900	249	22,8	70	222	235

Chamber volume	Charge TNT	Loading density	Chamber venting	Pressure	Shot
cm^3	g	kg/m^3	cm^2	bar	no.
10900	252	23,2	70	222	79
15200	475	31,3	70	300	215
15200	477	31,4	70	303	242
15200	490	32,2	35	307	19
7250	244	33,7	70	346	195
14100	594,5	42,1	35	483	53
10900	476	43,7	70	383	259
10900	476	43,7	70	500	189
10900	477	43,8	70	458	245
10900	477	43,8	70	395	258
15200	738	47,5	70	414	71
15200	738	48,5	70	385	250
15200	742	48,8	70	365	183
15200	741	48,8	70	475	249
15200	758	49,4	35	407	23
15200	759	49,9	35	388	26
7250	376	51,8	70	469	244
7250	376	51,8	70	450	254
7250	376	51,8	70	375	255
7250	371	52,1	70	438	196
7250	457	65,5	70	494	199
7250	476	65,6	70	760	252
7250	477	65,7	70	595	253
7250	477	65,8	70	590	256
7250	477	65,8	70	635	257
7250	477	65,8	70	629	198
15200	1005	67,5	35	707	27
10900	740	68,0	70	711	247

TABLE 5.1b. Average peak pressure for PETN detonated in a closed chamber

Shot no	Charge Weight Q^a (g)	Loading Density Q/V^a (kg/m^3)	Average Peak Pressure (bar)	Comment
70	21,5	1,25	20,6	b
60	26,5	1,54	26,5	b
67	36,5	2,11	32,6	b
61	51,5	2,98	49,5	b
68	52,5	2,98	42,9	b
71	51,5	2,98	41,3	b
62	76,5	4,42	67,8	b
63	101,5	5,86	86,8	b
64	151,5	8,76	120,8	b
65	201,5	11,56	142,5	b
72	101,5	23,60	258	c
73	201,5	46,86	436	c

a Includes a small contribution from blast cap no. 8, equivalent to about 1,5 g PETN.

b Chamber volume V = 17300 cm^3.

c Chamber volume V = 4300 cm^3.

TABLE 5.1c Average peak pressure for DYNAMITE detonated in a partly closed chamber:
Volume chamber V = 17300 cm^3, venting area A = 35 cm^2.

Shot no	Charge Weight Q[a] g	Loading Density Q/V[a] kg/m^3	Average Peak Pressure bar
28	87,5	5,07	40,0
24	88,5	5,13	39,4
29	176,5	10,2	80
30	439,5	25,5	225
31	876,5	50,8	471

[a] Includes a small contribution from blast cap no 8, equivalent to about 1,5 g dynamite.

TABLE 5.1d Average peak pressure versus loading density for RDX, COMP.B, AN/FO, and ALUMIT detonated in a closed chamber.

Shot no.	Type of Explosive	Charge Weight Q^a (g)	Loading Density Q/V^a (kg/m^3)	Average Peak Pressure (bar)	Comment
35	RDX	209,5	12,1	87,5	b
36	COMP.B	209,5	12,1	105,7	b
37	AN/FO	209,5	12,1	79,9	b
48	AN/FO	109,5	25,5	157,7	c
49	AN/FO	209,5	48,7	290	c
39	ALUMIT	209,5	12,1	87,5	b
50	ALUMIT	109,5	25,5	172	c
51	ALUMIT	209,5	48,5	224	c

a Includes 8 g TNT and blast cap no. 8, equivalent to about 1,5 g TNT.

b Chamber volume 17300 cm^3.

c Chamber volume 4300 cm^3.

TABLE 5.2a. Average peak pressure, maximum rate of pressure rise, and rise-time for burning of PETN in a closed chamber.

Shot (no)	Weight Q (g)	Loading Density Q/V (kg/m3)	Average Peak Pressure[a] p (bar)	Max. Rate of Pressure Rise (bar/ms)	Rise-Time[b] t_r (sec)	
11	10	0,58	2,3	$3,6 \cdot 10^{-3}$	1,2	c
12	25	1,45	3,0	$2,5 \cdot 10^{-3}$	2,7	c
13	50	2,89	6,7	$1,0 \cdot 10^{-2}$	3,2	c
14	100	5,78	22	$1,2 \cdot 10^{-2}$	6,4	c
16	200	11,7	95	4,4	4,8	c
17	400	23,1	230	11,8	3,3	c
44	100	23,3	e		-	d
45	200	46,5	e		-	d

a Corrected for small contribution (< 1 bar) due to the tracer composition used to ignite the PETN.

b Defined as the time from which a significant pressure increase is detected (approx. greater than 1% of average peak pressure) until average peak pressure is reached. (See Fig. 2.2)

c Volume of closed vessel V = 17300 cm^3

d Volume of closed vessel V = 4300 cm^3

e Incomplete burning - approximately 30% of PETN remained.

TABLE 5.2b Average peak pressure, maximum rate of pressure rise, and pressure rise time for burning of various explosives in a closed chamber. (Volume = 17300 cm^3).

Shot no	Type of Explosive	Weight (g)	Loading Density (kg/m^3)	Average Peak Pressure (bar)	Max. Rate of Pressure Rise (bar/ms)	Rise-Time t_r (Sec)
23	AN/FO	100	5,78	a	a	a
22	RDX	100	5,78	71[b]	1,3	0,7
24	ALUMIT	100	5,78	a	a	a
25	DYNAMITE	100	5,78	10[b]	$6,25 \times 10^{-3}$	25
26	COMP.B	100	5,78	50[b]	$1,25 \times 10^{-1}$	1,1
20	TNT	200	11,56	56[b]	$5,3 \times 10^{-2}$	5,6
21	TNT	400	23,12	163[b]	2,0	3,6

[a] No ignition using the tracer composition.

[b] Corrected for a small contribution ($\simeq$ 1 bar) due to the tracer composition used to ignite the explosives.

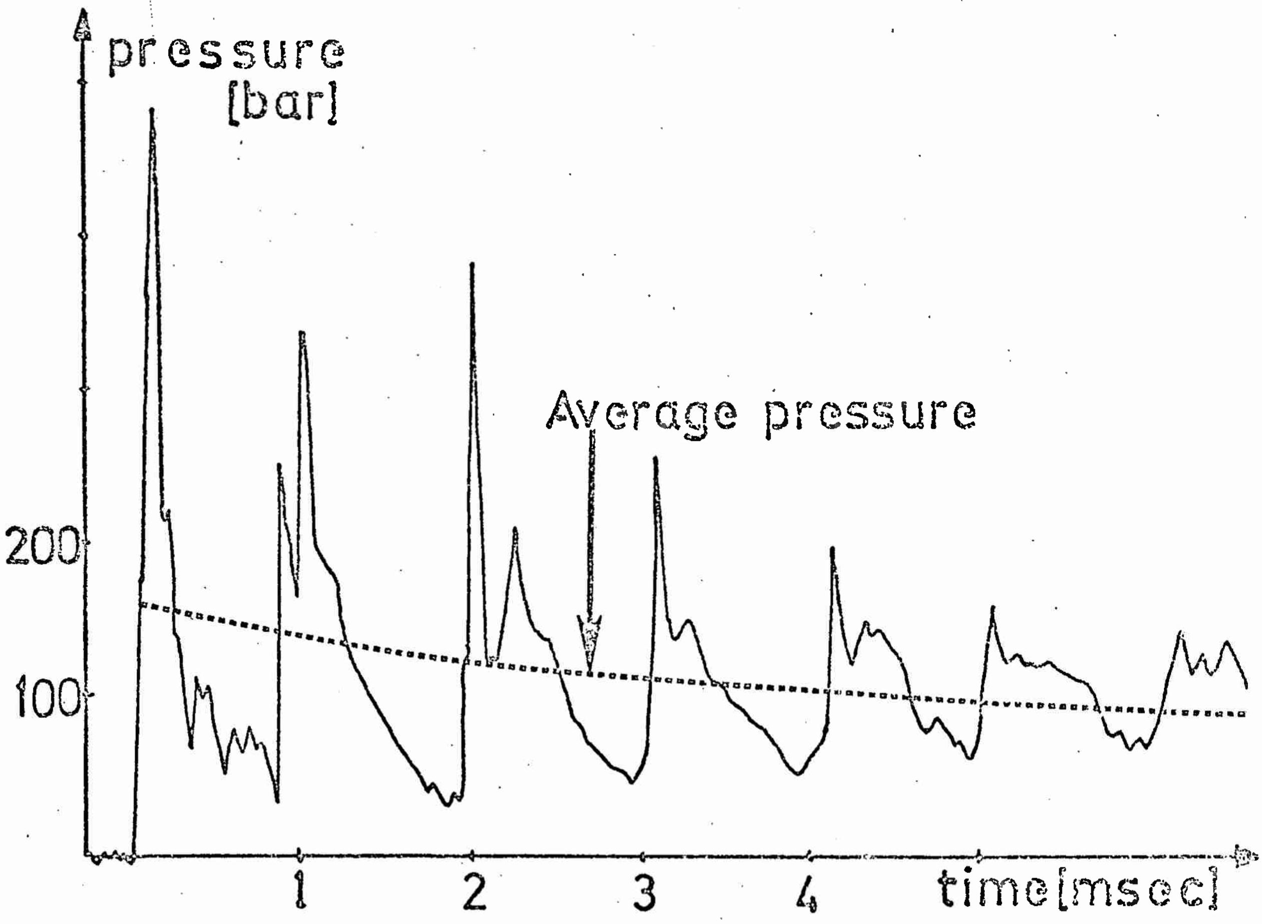
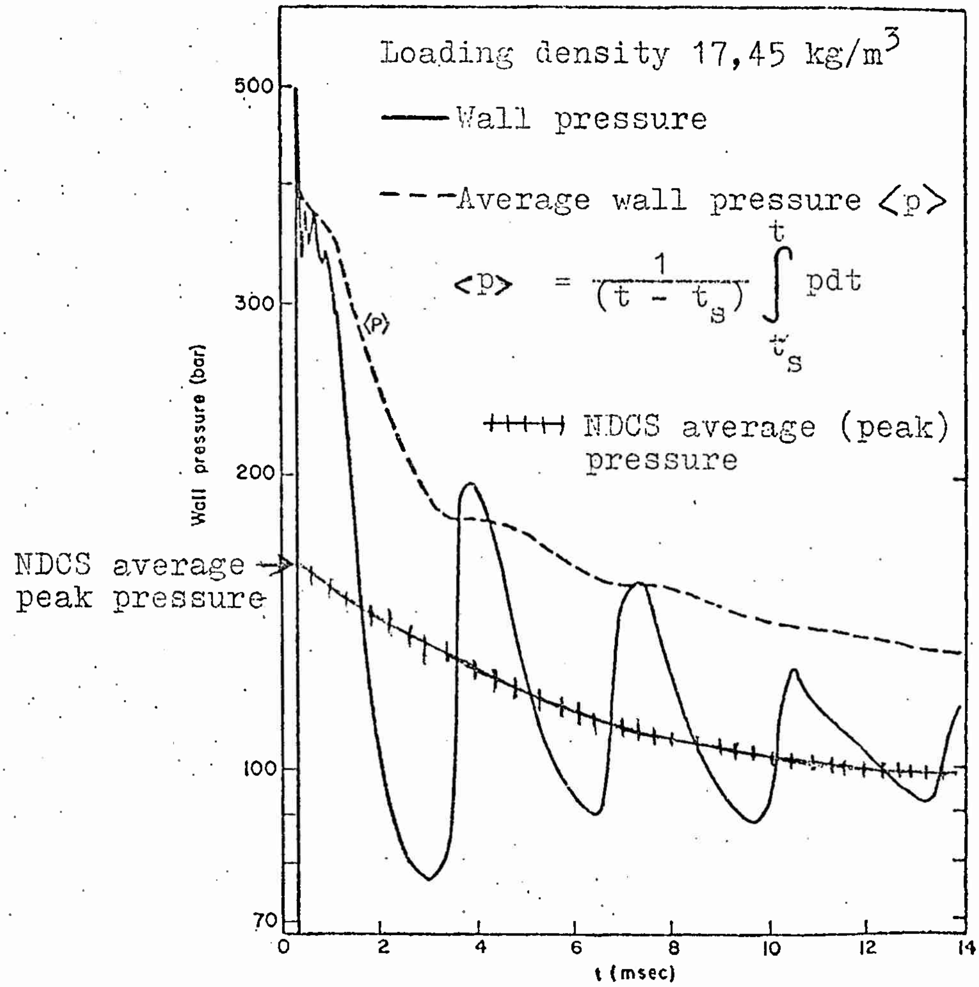


Fig. 2.a. Typical pressure-time record in a closed bomb detonation (PETN, 11,6 kg/m^3).



Wall pressure and average wall pressure versus time for a 450-kg charge of Pelletol detonated in an evacuated cavity, radius 1.83 meters.

Fig 2.b. Brode's definition of average wall pressure /11/ and the average peak pressure as defined for the result in this report.

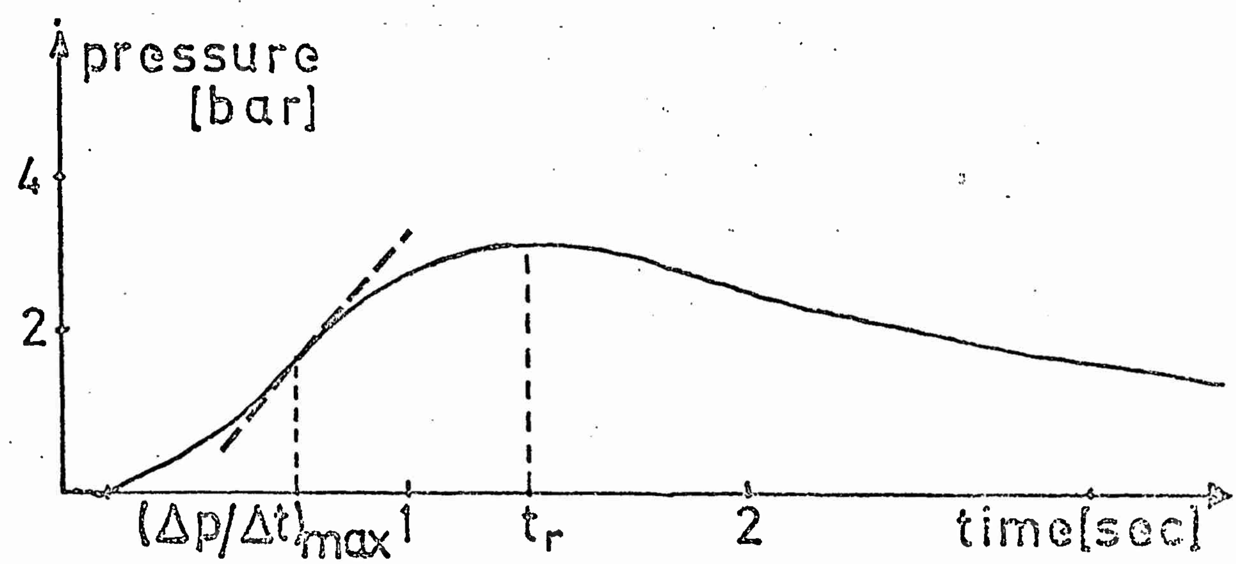


Fig. 2.c. Typical pressure-time record for closed bomb burning (PETN, 0,58 kg/m3).

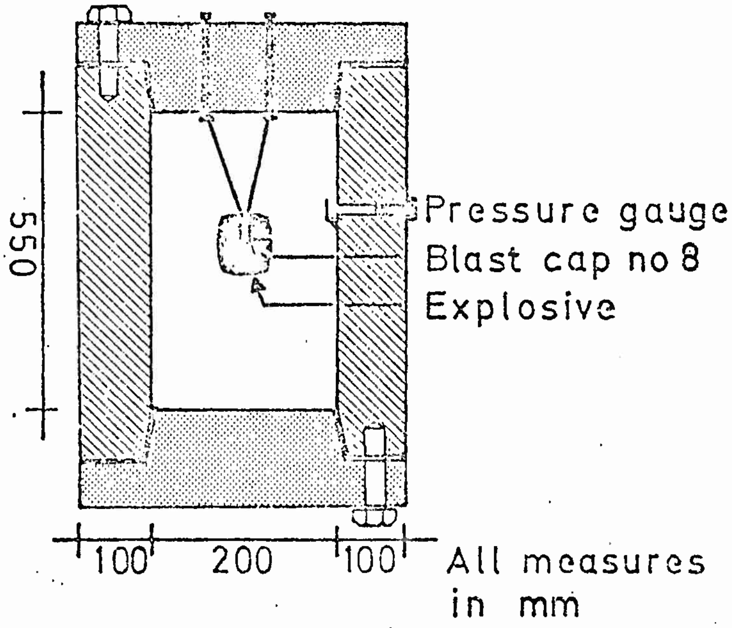


Fig. 4.2a. Closed bomb chamber and experimental details in the detonation tests.

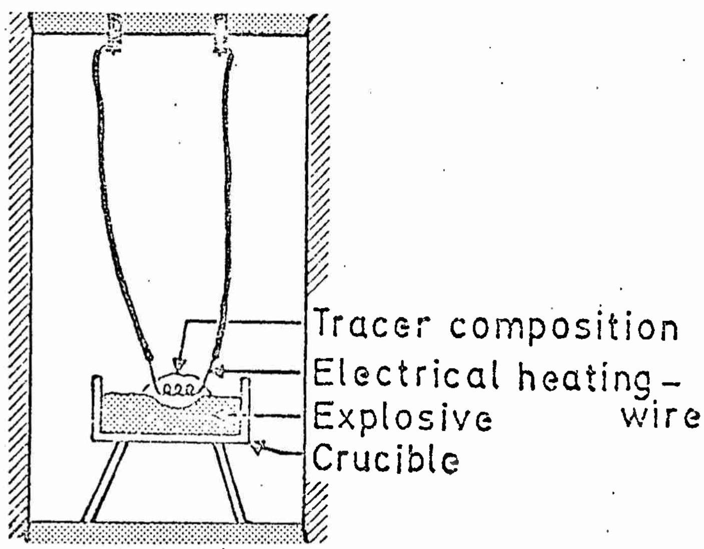


Fig. 4.2b. Closed chamber and experimental details in the ignitability tests.

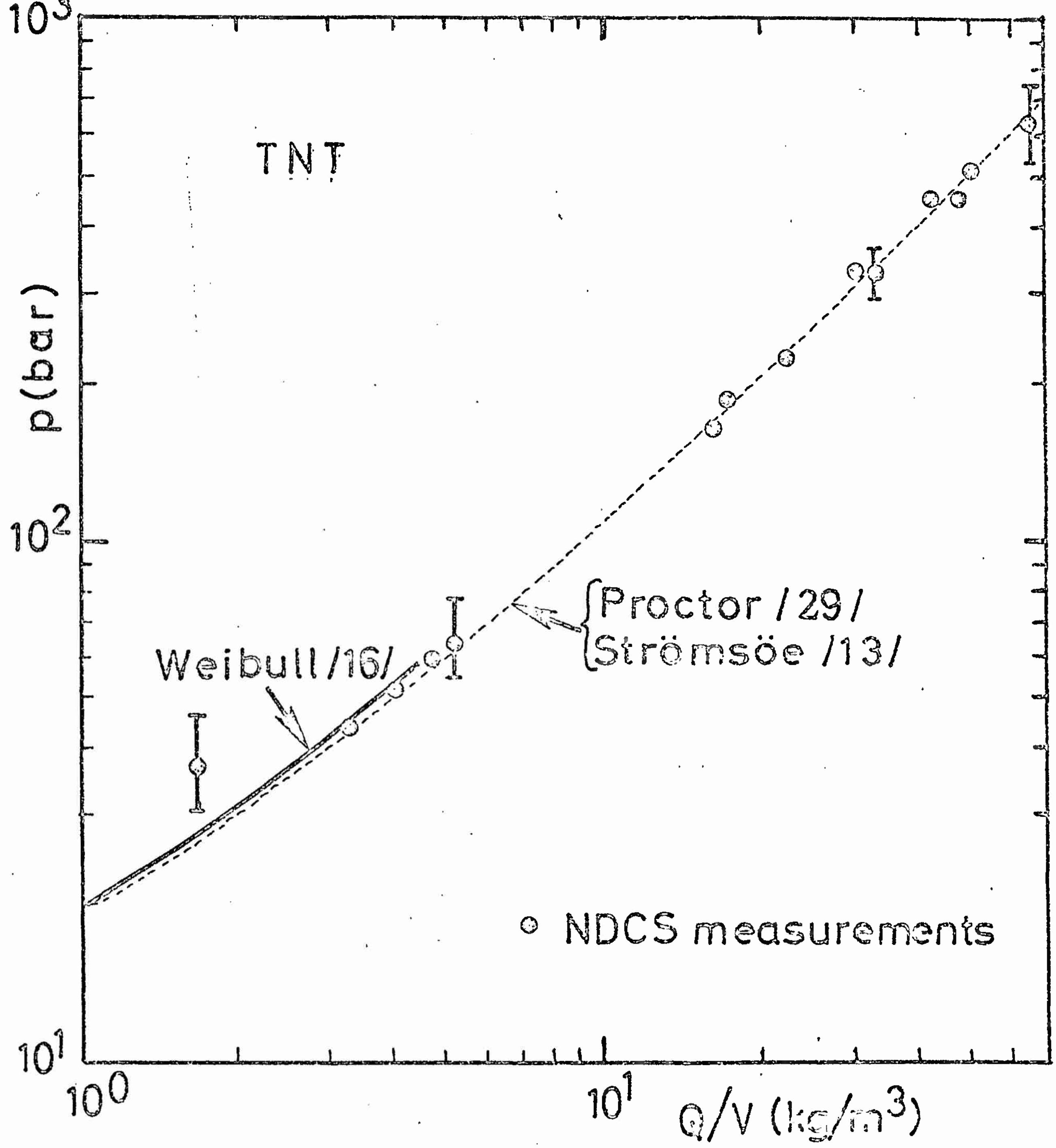


Fig. 5.1a. Average peak chamber pressure versus loading density for detonation of TNT.

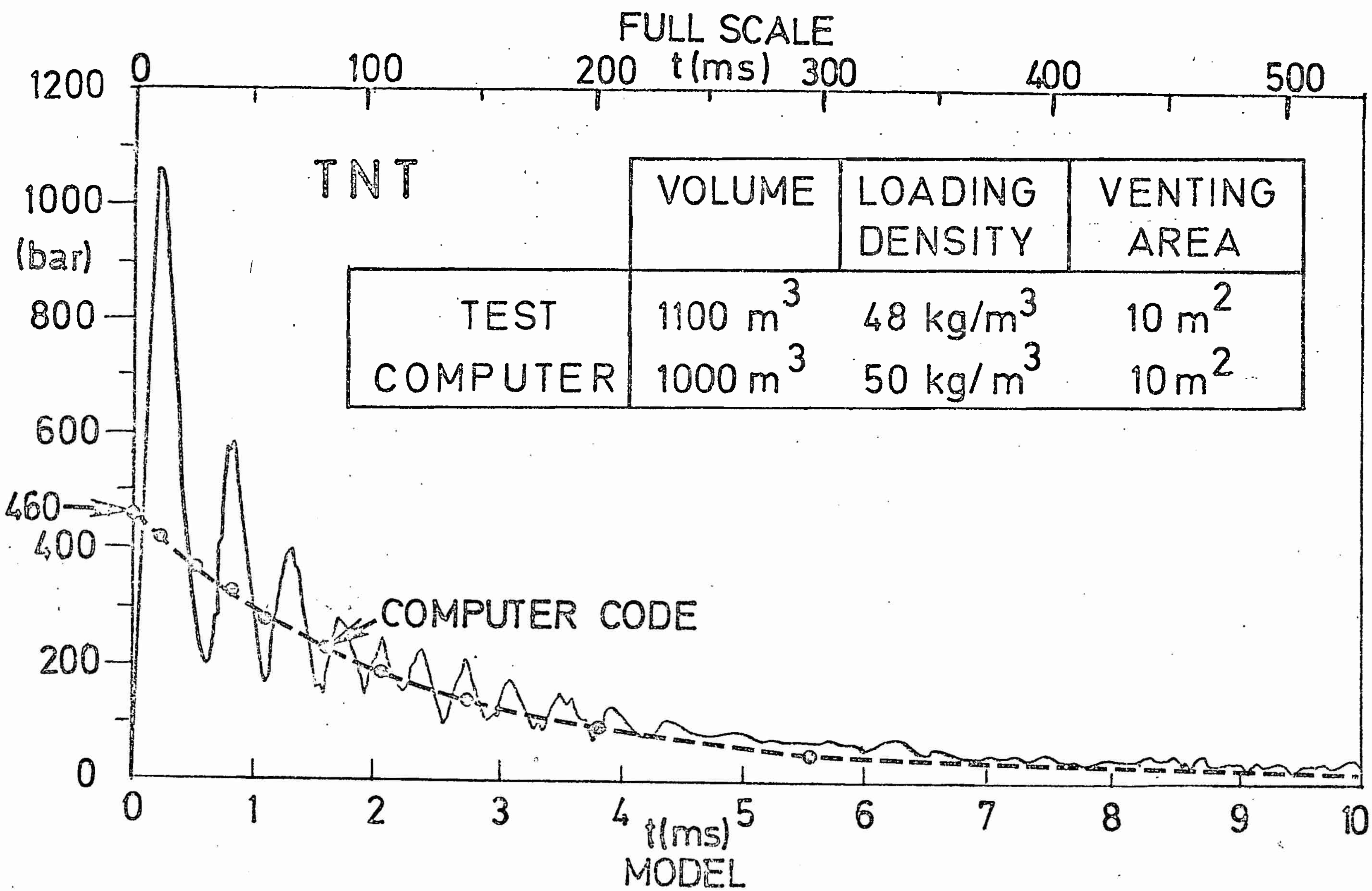


Fig.5.1b. Pressure-time record of chamber pressure (using an electrical low pass filter of $\simeq$ 1 kHz) for detonation of TNT with a loading density Q/V = 48 kg/m3. The chamber volume was V = 7250 cm3 (1100 m3) and venting area A = 35 cm2 (10 m2), with numbers in parenthese indicating the full scale case. The results from the computer code /24/ were obtained for a case where Q/V = 50 kg/m3, V = 1000 m3, and A = 10 m2.

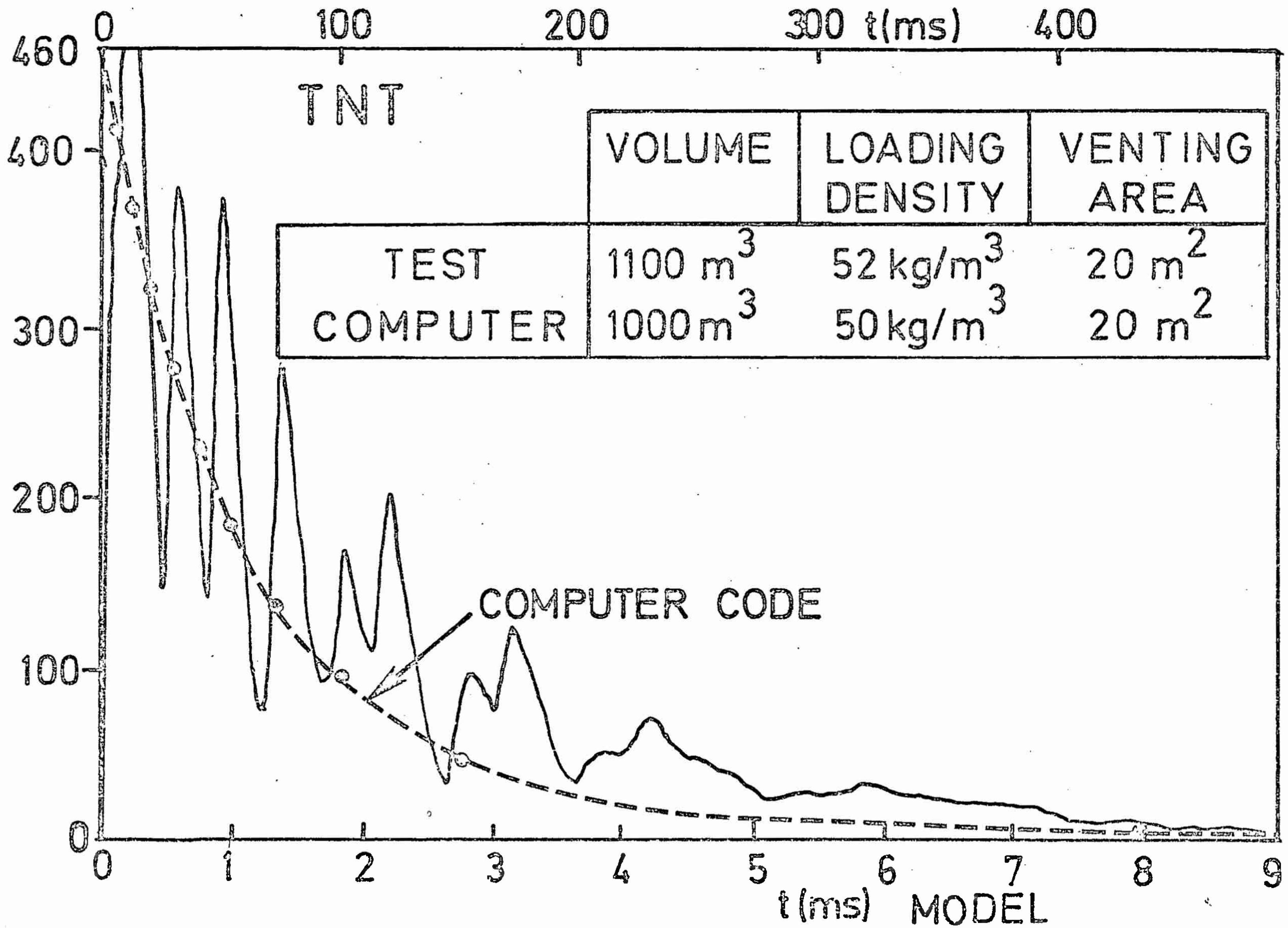


Fig.5.1c. Pressure-time record of chamber pressure (using an electrical low pass filter of ≃ 1 kHz) for detonation of TNT with a loading density Q/V = 52 kg/m3. The chamber volume was V = 7250 cm3 (1100 m3) and venting area A = 70 cm2 (20 m2), with numbers in parenthese indicating the full scale case. The results from the computer code /24/ were obtained for a case where Q/V = 50 kg/m3, V = 1000 m3, and A = 20 m2.

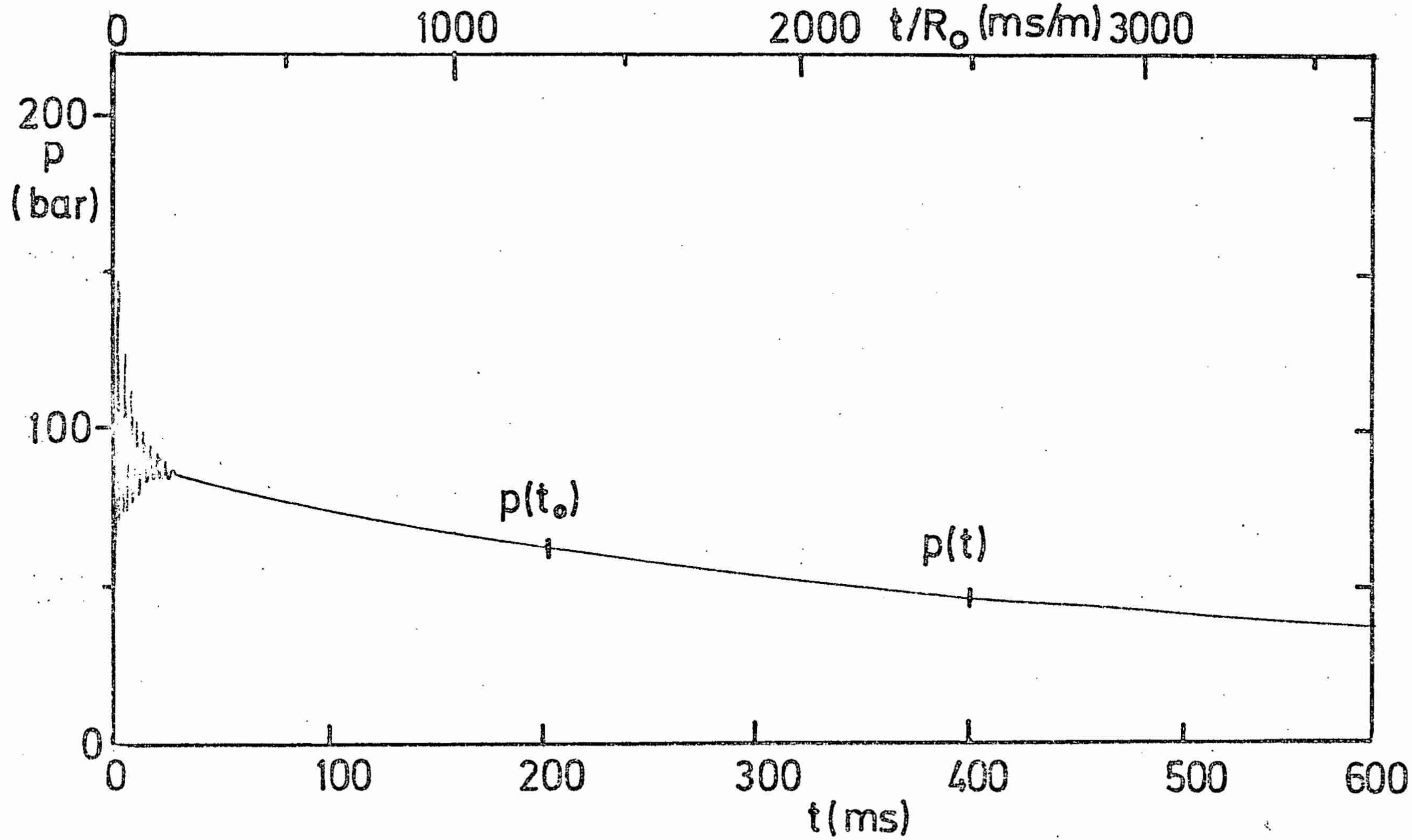


Fig.5.1d Pressure-time record of chamber pressure for detonation of TNT in a closed chamber with a loading density of 11,6 kg/m3. The pressure decrease can be roughly described as $p(t) = p(t_o) \exp[-0{,}00023\ (t - t_o)/R_o]$. Here, $R_o = 0{,}160$ m is the radius of an equivalent spherical cavity corresponding to V = 17300 cm3.

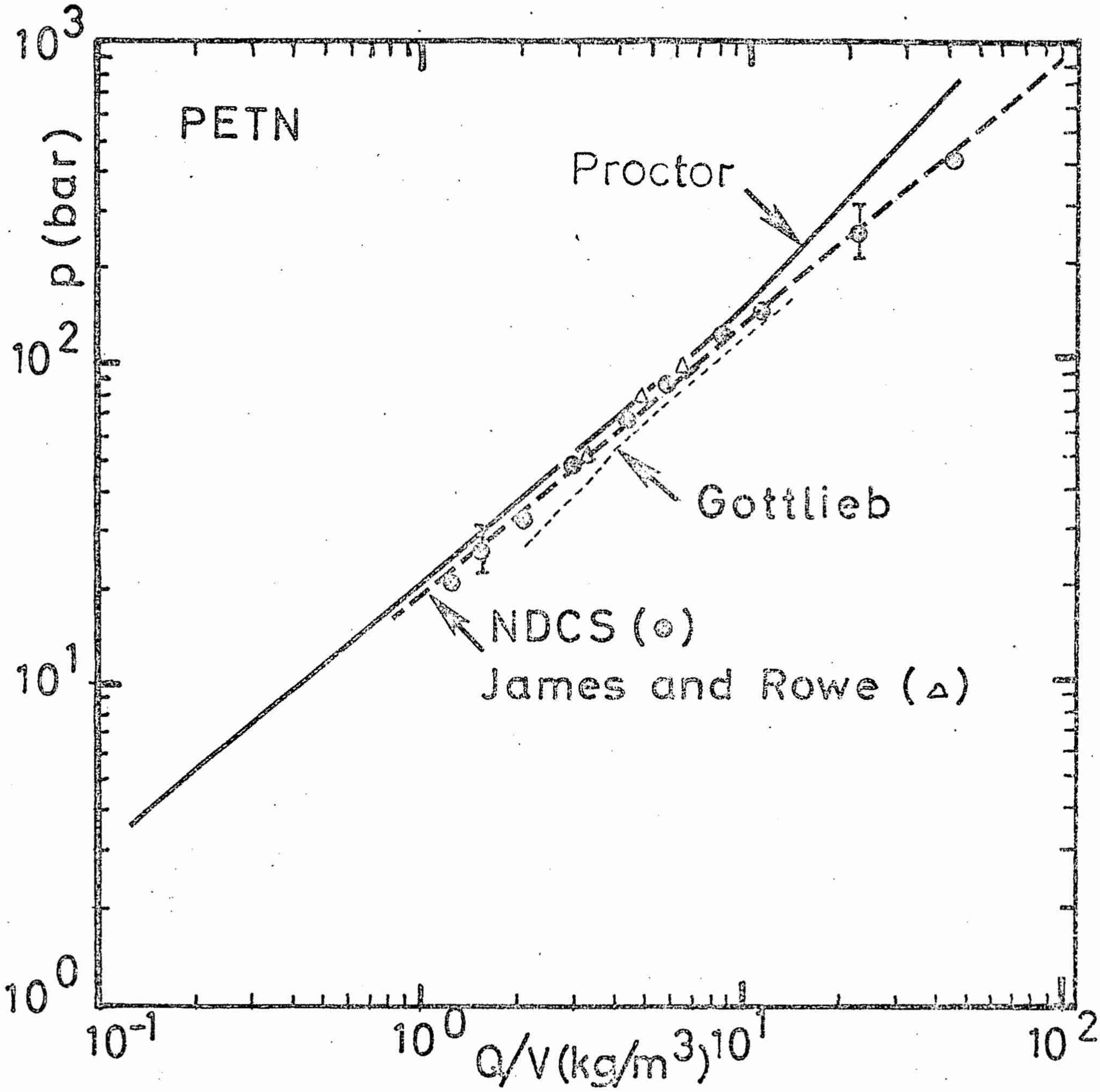


Fig. 5.1e. Average peak chamber pressure versus loading density for detonation of PETN versus loading density. The experimental results by Gottlieb /10/ and James and Rowe /17/ as well as the theoretical results by Proctor /29/ are also included in the figure.

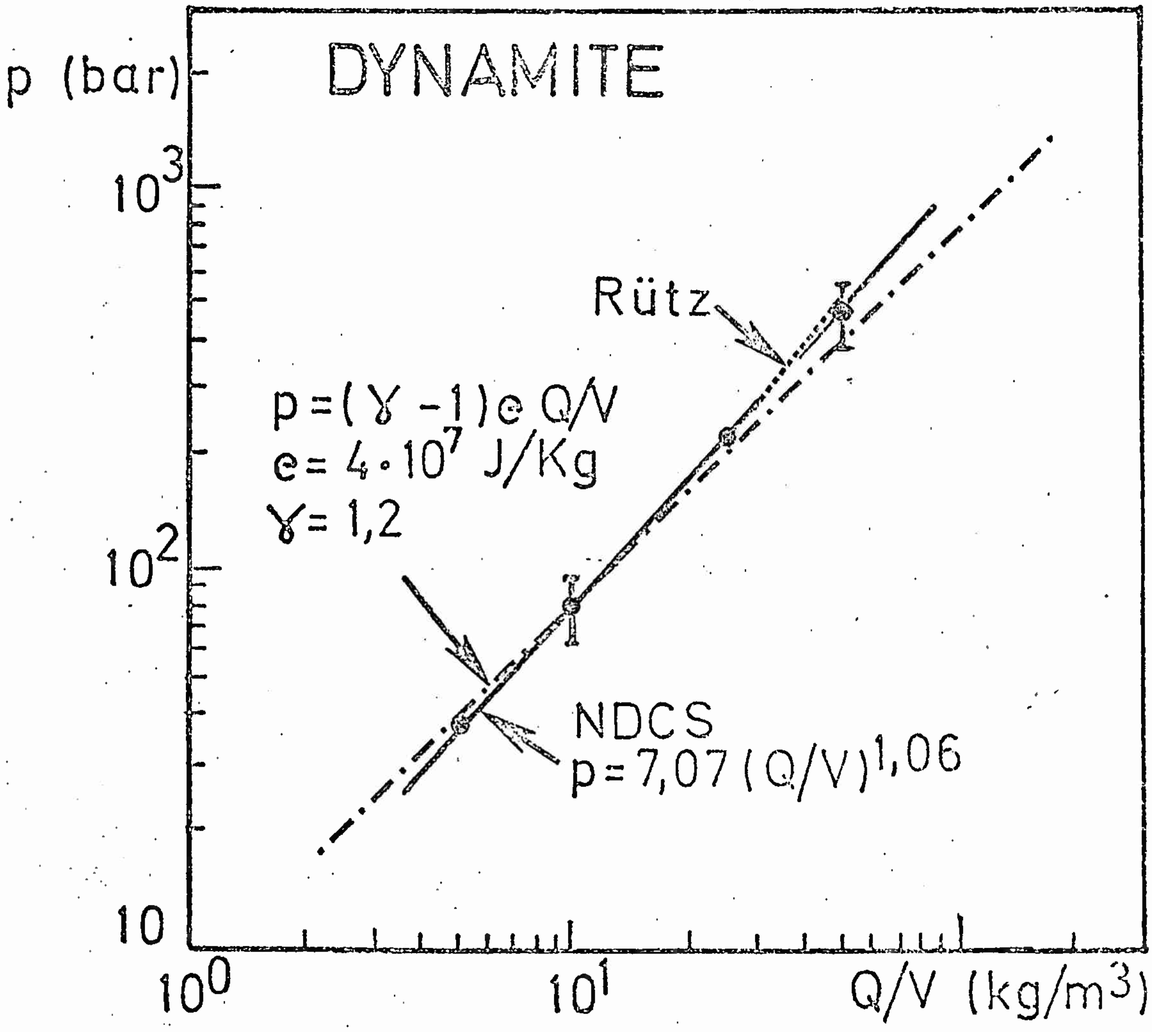


Fig. 5.1f. Average peak chamber pressure versus loading density for detonation of dynamite. The continuous line is the best fit to the data with $p = 7{,}07\ (Q/V)^{1{,}06}$, which is in excellent agreement with the experimental results reported by Rütz /27/. The theoretical relationship $p = (\gamma - 1)\ e\ Q/V$ [Eq.(3.1)] reproduces the data to a good approximation using $e = 4 \times 10^7$ J/kg and $\gamma = 1{,}2$.

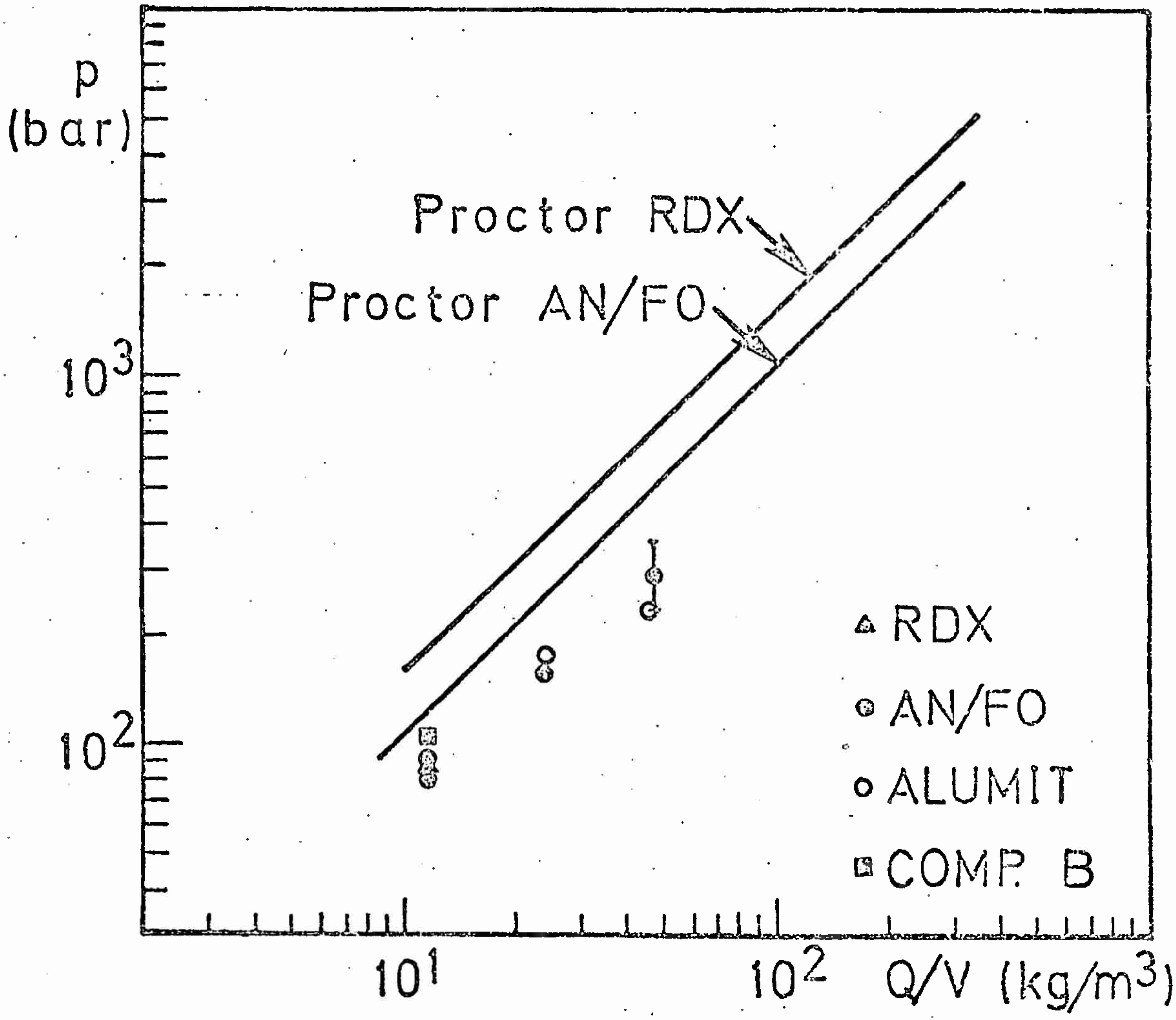


Fig 5.1g. Average peak chamber pressure for a limited range of loading densities for detonation of RDX, AN/FO, ALUMIT, and COMP.B. The theoretical calculations by Proctor /24/ are considerably higher than the experimental results, but this may be due to experimental uncertainties.

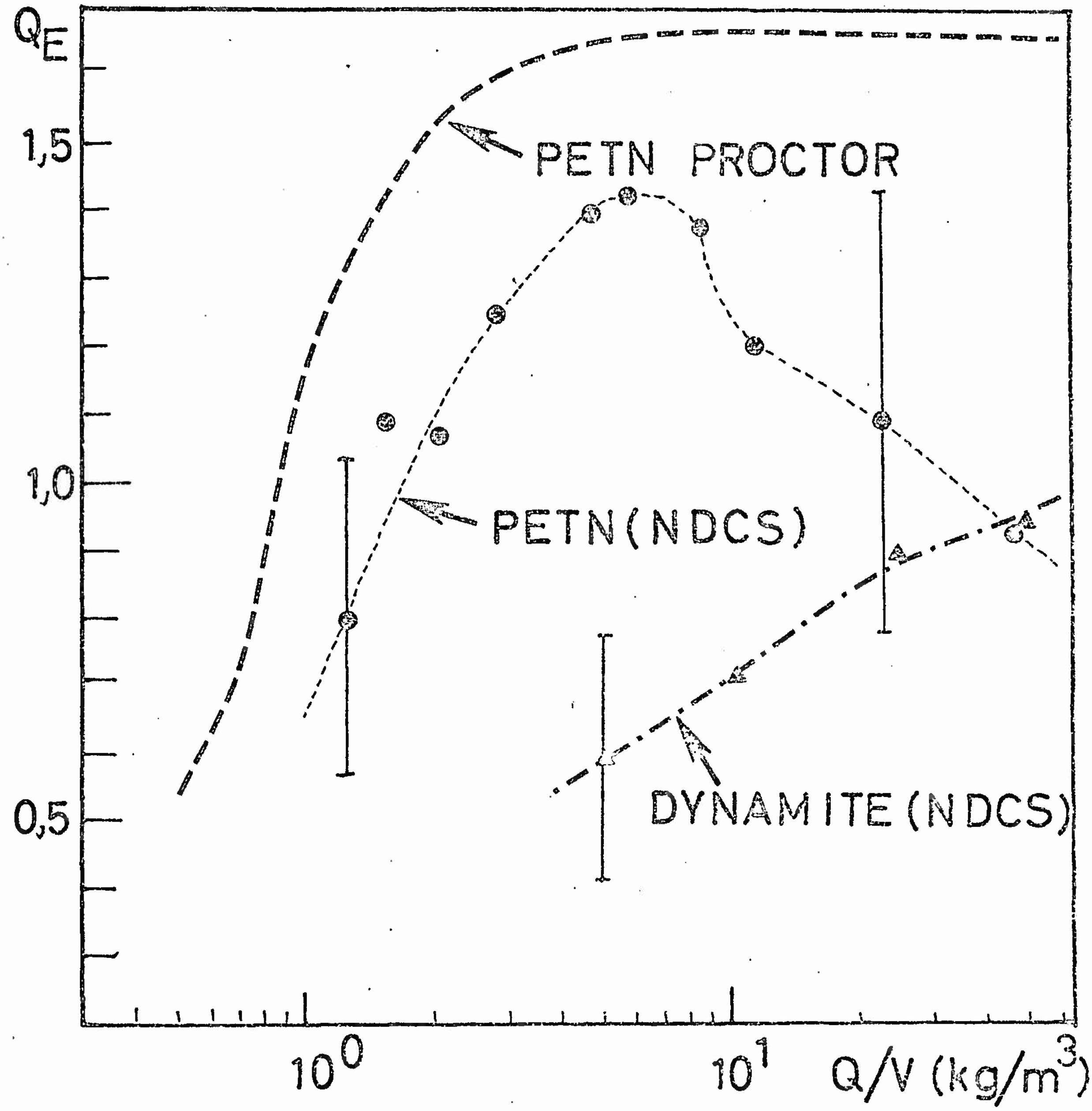


Fig. 5.1h. TNT equivalence Q_E of PETN and DYNAMITE versus loading density as determined from Figs. 5.1a - 5.1c. The results based on theoretical calculations by Proctor /29/ are also included in the figure.

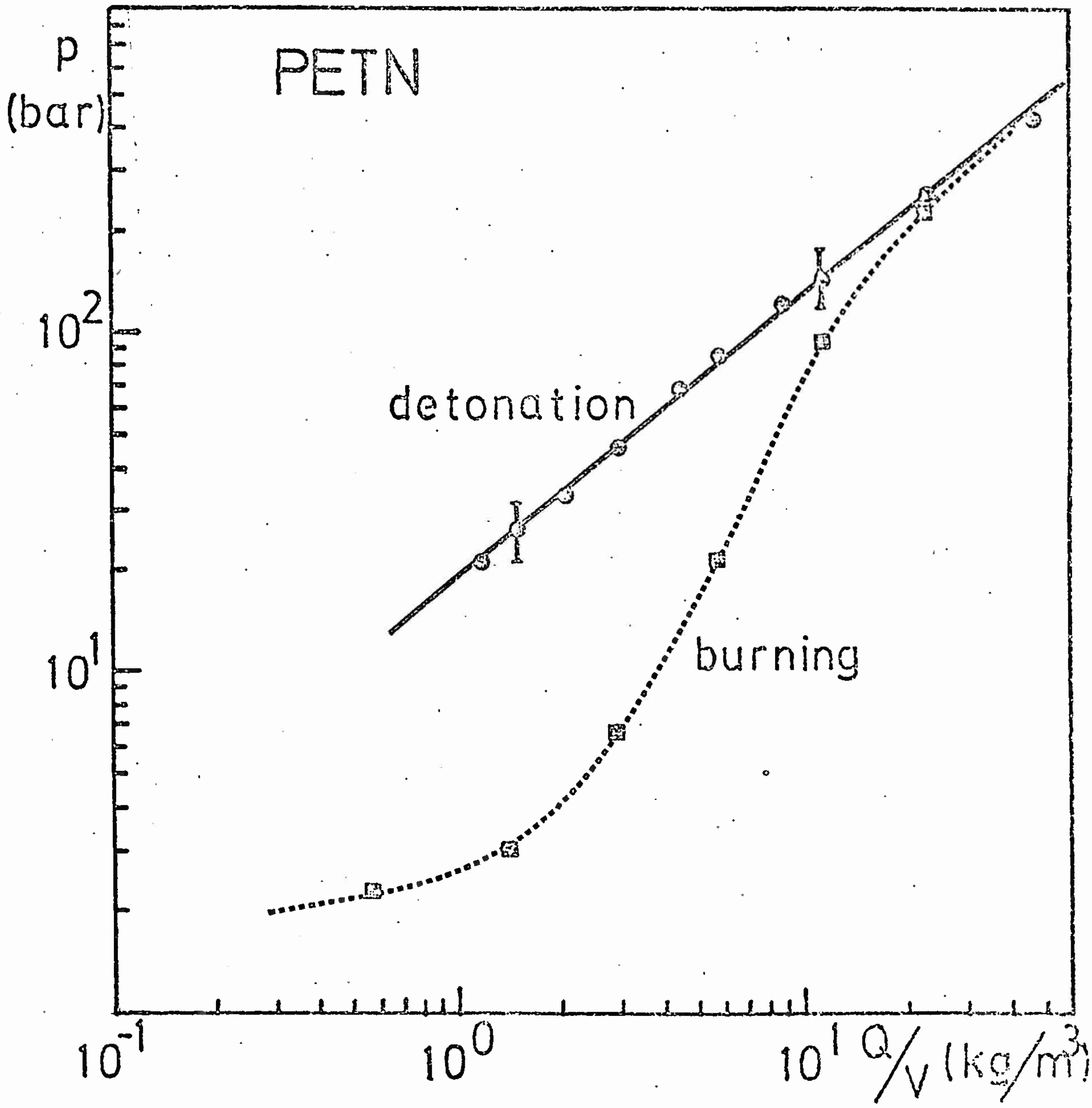


Fig.5.2a. Peak chamber pressure versus loading density for detonation and burning of PETN versus loading density. For the highest loading densities the burning has the character of a detonation.